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Tectonic geomorphology and paleoseismology of the Surigao segment of the Philippine fault in northeastern Mindanao Island, Philippines

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ABSTRACT

The Philippine fault is a major strike-slip fault that traverses the entire Philippine archipelago for more than 1250 km and has generated at least 10 surface rupturing earthquakes for the past 200 years. To better understand its characteristics, we have conducted review of historical earthquakes, tectonic geomorphic mapping and paleoseismic trenching along the 100-km-long Surigao segment, the northernmost segment of the Philippine fault on Mindanao Island. We mapped the Surigao fault based on aerial photographs and identification of well-defined geomorphic features in the field. Combining this with historical accounts and paleoseismic trenching, we have identified and mapped the surface rupture of the 1879 M_w 7.4 Surigao earthquake. Paleoseismic trenching conducted at two sites also led us to identify evidence of at least four surface-rupturing earthquakes including the 1879 event during the past 1300 years.

1. Introduction

The Philippine fault is a sinistral strike-slip fault traversing the entire length of the Philippine archipelago for a distance of ~1250 km from northern Luzon Island southward to eastern Mindanao Island (Allen, 1962; Aurelio, 2000; Barrier et al., 1991; Rangin et al., 1999; Tsutsumi and Perez, 2013) (Fig. 1a). This NNW-trending, arc-parallel fault is a consequence of the oblique subduction of the northwest-moving oceanic Philippine Sea plate beneath the Philippine archipelago (Aurelio, 2000; Fitch, 1972). Based on interpretation of aerial photographs and satellite images, field surveys and seismicity, this fault was found to be one of the most important active tectonic structures in the western Pacific region with pronounced tectonic geomorphic features such as fault scarps, offset streams, elongated depressions, sag ponds, and pressure and shutter ridges (Allen, 1962; Aurelio et al., 1991; Barcelona, 1981; Nakata et al., 1977; Pinet and Stephan, 1990; Pubellier et al., 1991, 1993; Quebral et al., 1996; Ringenbach et al., 1993; Rutland, 1968; Tsutsumi and Perez, 2013).

The Philippine fault has been seismically active for the past two centuries with more than 10 earthquakes greater than *M* 7 (Bautista and Oike, 2000) (Fig. 1a). The 1990 M_s 7.8 central Luzon earthquake was the largest and most destructive earthquake accompanied by about 120-km-long surface rupture with 6 m maximum left-lateral displacement (Nakata et al., 1996) (Fig. 1a). Other recent surface-rupturing earthquakes along the Philippine fault are the 1973 M_L 7.0 Ragay Gulf earthquake (Morante, 1974; Tsutsumi et al., 2015) and the 2003 M_s 6.2 Masbate earthquake (PHIVOLCS Quick Response Team, 2003) (Fig. 1a).

The high seismic potential of the Philippine fault can also be recognized from recent campaign-type GPS observations that showed very high slip rates ranging from 20 to 30 mm/year along the different segments of the fault (Aurelio, 2000; Barrier et al., 1991; Galgana et al., 2007). From the perspective of a long-term earthquake risk assessment, there is a need to study the Philippine fault because the fault passes through or is close to major population centers in the country. However, basic information to conduct this assessment for the Philippine fault, such as the exact locations of surface traces, slip rates and recurrence intervals of surface-rupturing earthquakes, are still poorly known. Historical records of large earthquakes in the Philippines date only back to the end of the 16th century and instrumental seismic monitoring started only in the latter part of the 19th century (Bautista, 1999; Bautista and Oike, 2000; Repetti, 1946; SEASEE, 1985). Paleoseismic studies in the Philippines started in 1992 wherein the focus of the study has been the active fault traversing Metropolitan Manila, the capital of the Philippines, (Nelson et al., 2000) and segments of the Philippine fault in Luzon and Masbate Island (Fig. 1a) (Daligdig, 1997, Tsutsumi et al., 2006; Tsutsumi et al., 2015; Papiona and Kinugasa, 2008). Thus, additional

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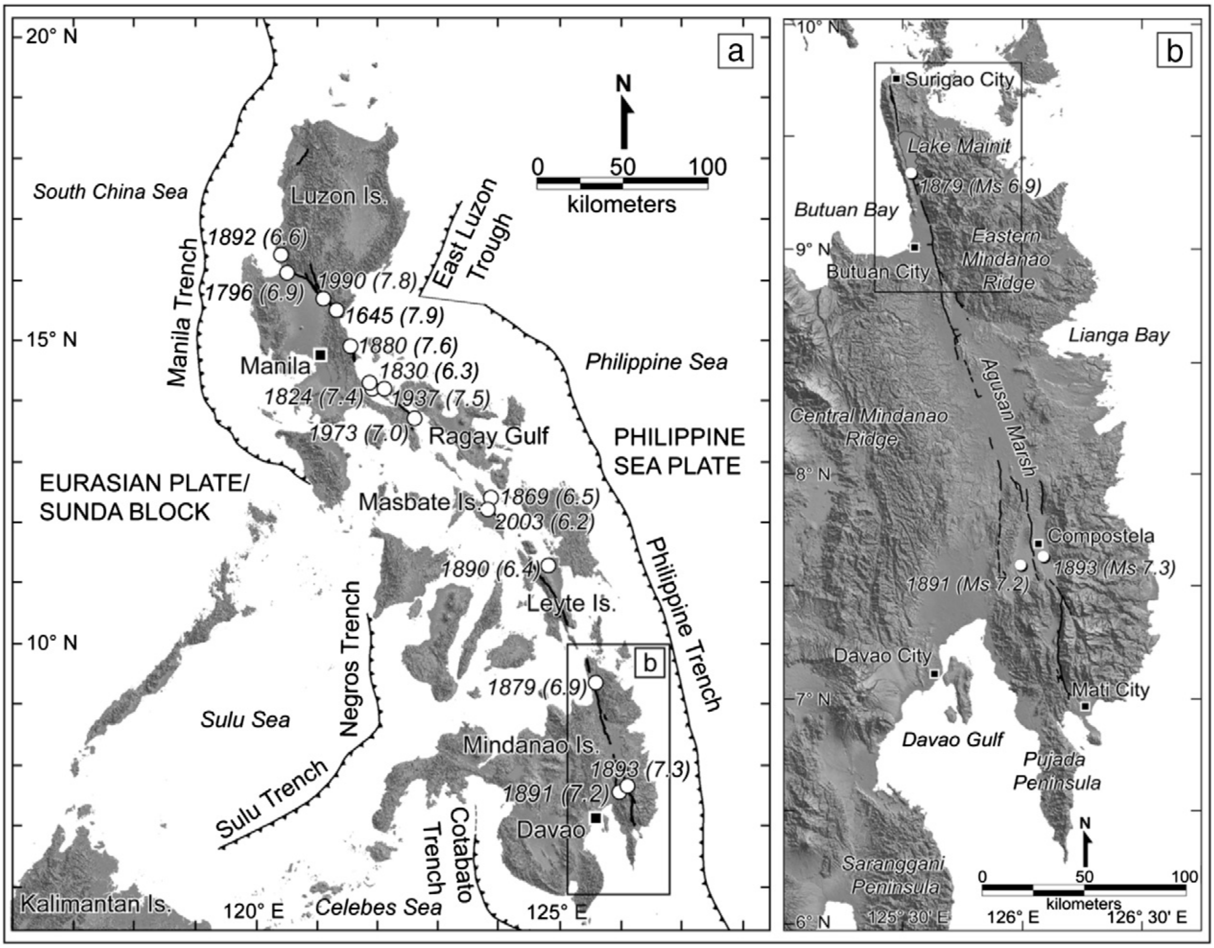

Fig. 1. The seismotectonic setting of eastern Mindanao, Philippines. (a) Map showing the tectonic structures around the Philippine archipelago, the Philippine fault and epicenters (circles) of moderate to large magnitude earthquakes ($M > 6$) along the Philippine fault from 1700 to 2012 (other active faults are not shown for simplicity). The rectangle shows the location of panel b. (b) Map showing the Philippine fault and epicenters of surface-rupturing earthquakes in eastern Mindanao Island. Circles are epicenters of historical earthquakes with surface rupture. The rectangle shows the location of Fig. 2. The trace of the Philippine fault is from Tsutsumi and Perez (2013) while the epicenters are from SEASEE (1985) and Bautista and Oike (2000).

paleoseismological data are essential to augment the limited historical and instrumental data for a better assessment of seismic hazards related to the Philippine fault.

Compared to the other segments, there were few geological studies for the Philippine fault in Mindanao Island (Fig. 1a and b). Its surface trace location and geometry were poorly known because the fault mostly traverses the alluvial lowland and low-lying hills under thick vegetation. Tsutsumi and Perez (2013) mapped the entire length of the Philippine fault on land including Mindanao Island (Fig. 1a and b) on 1:50,000-scale topographic maps by interpreting stereographic pairs of ~1:30,000-scale aerial photographs. Perez et al. (2015) described the distribution of the Philippine fault in Mindanao Island and suggested that the Philippine fault is composed of several segments that are divided by geometric discontinuities such as en echelon steps, bends, changes in strike, gaps and bifurcation in the surface trace.

In this paper, we present the result of geological, geomorphological and paleoseismological studies on the ~100-km-long Surigao segment, the northernmost segment of the Philippine fault in Mindanao Island (Figs. 1b and 2).We interpreted 1:30,000-scale aerial photographs taken in 1979 and acquired from the National Mapping Resource and Information Authority (NAMRIA) of the Philippine government. After this, we conducted geological field investigation along the Surigao segment and identified the surface rupture associated with the 1879 Surigao earthquake. We also reviewed the historical seismicity of the island based on published earthquake catalogues and historical documents (Bautista, 1999; Bautista and Oike, 2000; PHIVOLCS, 2012; Repetti, 1946; SEASEE, 1985). We then excavated paleoseismic trenches at two sites and identified evidence of at least two and probably four surface-rupturing earthquakes during the past 1300 years.

2. Tectonic and geologic setting

The Philippine archipelago is part of a wide convergence zone between the Sunda block (an independent part of the Eurasian plate) and the Philippine Sea plate (Fig. 1a). East of the Philippine archipelago, the Philippine Sea plate subducts beneath the archipelago along the Philippine trench (4°–15°N) (Cardwell et al., 1980; Fitch, 1972; Hamburger et al., 1983) (Fig. 1a). On the western side of the archipelago, the Sunda block is being subducted from the west along the Manila trench (13°–22°N), the Negros-Sulu trench system (6°–10°N) and the Cotabato trench (4°–7°N) (Cardwell et al., 1980; Hamilton, 1979). Fitch (1972) suggested a shear partitioning model for the formation of the Philippine fault in between these two oppositely-dipping subduction zones. In this model, the Philippine trench accommodates the trench-normal component of motion, while the trench-parallel component is being accommodated by the Philippine fault. This model has been verified by analogue modeling (Pinet and Cobbold, 1992) and GPS measurements (Aurelio, 2000).

Mindanao Island is the second largest island in the Philippines and located in the southern part of the archipelago (Fig. 1a and b). Previous geologic studies revealed that the island can be divided mainly into two terranes based on lithologic and stratigraphic differences (Pubellier et